Системы телекоммуникации, связи и защиты информации

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Monitoring of integrity of concrete elements with arrays of optical fibers

We present a sensor system for monitoring the integrity of concrete structural elements such as beams and columns in buildings and other structures. The integrity sensors are arrays of conventional multimode telecommunications-grade optical fibers embedded in concrete elements. A sharp decrease in optical transmission indicates the breaking of the optical fiber, which is typically caused by a crack or destruction of the structural element. This sensor system successfully detected cracks in concrete beams under load. Due to its effectiveness and simplicity, it has many potential applications as cost-effective alternative to more precise but sophisticated and expensive systems for structural health monitoring.

Описана система для обнаружения трещин, , которые могут возникать в структурных элементах из бетона, таких как балки, столбы и колонны. Система использует пучки волоконных световодов залитые в бетон при его изготовлении. Резкое уменьшение интенсивности оптического сигнала указывает на разрыв световода и является признаком появления трещины. В эксперименте, эта система успешно обнаруживала трещины в бетонных балках подверженых нагрузкам. Технически и экономически, эта система представляет эффективную альтернативу более точным, но сложным и дорогим существующим системам контроля состояния и целостности зданий и сооружений.

Ключевые слова: *волоконные световоды, волоконно-оптические датчики, контроль целостности структур, структурные элементы из бетона*

Introduction

In recent years, a variety of optical fiber sensor systems were developed for structural monitoring. A number of such systems are already installed in bridges and other structures all over the world [1-3]. The dominant type of sensor in this application is the Fiber Bragg Grating (FBG) [3-6]. The FBG sensors measure strain, torsion, bending, temperature and other characteristics, which allow for health monitoring of the structures. The FBG sensors are relatively expensive. In addition, FBG sensor systems require the so-called interrogators which are rather complex and expensive. This factor limits the wide spread of FBG-based structural health monitoring. On the other hand, in many cases it is just sufficient to know if the structure is damaged or not. For example, it is crucial to know which columns and beams of a building have a significant damage and which not, after an earthquake. For such applications, some simple and non-expensive technical means would be of great practical interest. In this work, we present a sensor system which employs arrays of conventional telecommunications-grade optical fibers embedded in concrete structures. The technique is destructive in the sense that the optical fiber is destroyed together, with the structural element, and the respective sharp decrease in optical transmission indicates crack or total destruction of the respective structural element. Although the basic concept is simple, the practical implementation of such a system faces many challenges. Following is the description of some key elements of the system. This is followed by the experimental data on system behavior.

1. System concept

The layout of the generic sensor system is shown in Fig. 1. The light source (1) is coupled via convex cylindrical lens (2) which serves as a beam splitter to an array of conventional multimode communications-grade optical fibers (3) which are embedded in the concrete element (4). The optical fibers (3) extend all the way through the concrete element (4) up to the array of optical receivers (5), which in turn is connected to data acquisition and processing unit (6).

The light source (1) is a laser diode (Coherent VLM2, 4 mW @ 670 nm). The beam splitter (2) is a single biconvex cylindrical lens which expands the laser beam in one direction only. The beam is coupled to an array of optical fibers (3). /We employed

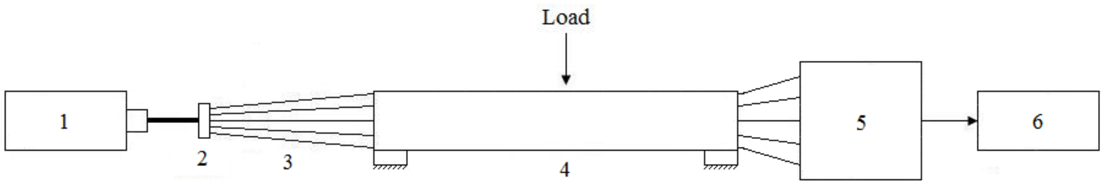


Fig. 1. Layout of the generic sensor system: (1) – optical source (diode laser), (2) – beam splitter, (3) – optical fibers, (4) – concrete element, (5) – array of optical receivers, (6) – digital oscilloscope

various types and models of optical fibers (see Section 3 for details)/. Each optical receiver (5) consists of a *p-i-n* photodiode (Quartz FD-263) and a transimpedance amplifier. The outputs of the optical receivers are multiplexed in the time domain and the respective electrical signals are stored in a digital oscilloscope (Tektronix TDS2024B). The amplitude of the signals is monitored continuously. A sharp decrease in optical transmission of one or several optical fibers of the array signifies the breaking of the fiber and, respectively, the breaking (crack) of the concrete element.

2. The choice of the optical fibers

The first choice to make is to decide which type of the optical fiber: the monomode or multimode has more advantages in the present application.

The monomode optical fibers are widely used in modern telecommunications systems. They are thin, lightweight and relatively cheap. But, the requirements for the quality of the light source and coupling elements are strict. Therefore, the cost of components is high and the fabrication, installation and maintenance of the monomode optical fiber sensor systems is complex and expensive.

The multimode optical fibers come in various diameters, refractive index profiles, types and numbers of protective coatings and jackets. Their bandwidth is much smaller than that of the monomode fibers, but this feature is of almost no importance in applications relating to characterization of mechanical structures. Due to the large core and angular aperture of the multimode optical fibers, they are compatible with the low-cost light emitting diodes and non-expensive connectors and other line components. The fabrication, installation and maintenance of the multimode optical fiber sensor system is relatively simple and non-expensive. In view of these advantages, we use the multimode fibers in our system. The types of the optical fibers, which we used in this work are given in the following Table 1.

The internal structure of optical fibers of FG and FT series is shown in Fig. 2.

Table 1. The optical fibers employed in the experiment

Parameter	FG-200 UCR	FG-200 LCR	FG-365 LEC	FT-200 URT	FT-400 URT	50/125 AFS	105/125 AFS
Diameter of the core	200 ± 8 μm	200 ± 8 μm	365 ± 14 μm	200 ± 5 μm	400 ± 8 μm	50 μm	105 μm
Diameter of the cladding	240 ± 5 μm	240 ±5 μm	400 ± 8 μm	225 ± 5 μm	425 ± 10 μm	125 μm	125 μm
Diameter of the coating	260 ±6 μm	260 ±6 μm	425 ± 10 μm	-----	-----	-----	-----
Diameter of the buffer	400 ± 30 μm	400 ± 30 μm	730 ± 30 μm	500 ± 30 μm	730 ± 30 μm	250 μm	250 μm
Numerical aperture	0.22 ± 0.02	0.22 ± 0.02	0.22 ± 0.02	0.48 ± 0.2	0.48 ± 0.03	0.22	0.22
Attenuation	12 dB/km @ 850 nm	12 dB/km @ 850 nm	12 dB/km @ 850 nm	12 dB/km @ 820 nm	12 dB/km @ 820 nm	-----	-----

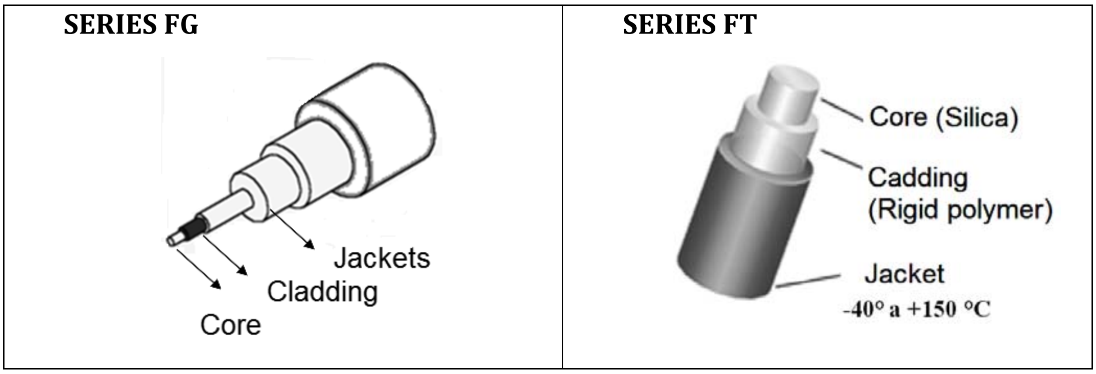


Fig. 2. Internal structure of multimode optical fibers of FG and FT series

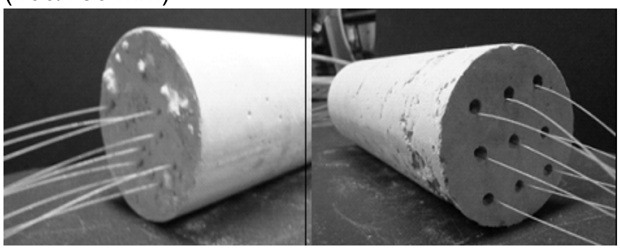
3. Embedding the optical fibers in the concrete elements

Production of concrete elements involves many factors that can cause damage to optical fibers. In particular, coarse aggregates such as gravel can break the optical fibers when filling the mold with fresh concrete mix. Therefore, the optical fiber sensors are usually installed at the surface of already fabricated concrete elements. There are few works on actually embedding the optical fibers in fresh concrete mix [2, 7-8]. In these works, some protection in a form of tubes, sleeves and sheets of plastic or metal are used for protecting the optical fibers during the fabrication of concrete elements. However, such a protection may mask the effect of crack in the concrete element during structural health monitoring. Therefore, we tried embedding the optical fibers in concrete elements with no special protection. In addition, we tried protecting the fibers temporarily while filling the mold with fresh concrete mix. We put the optical fibers in plastic tubes of small diameter when filling the mold with concrete mix. The tubes were removed after filling the mold when the mix was still fresh. With both of these techniques, some fibers were damaged and lost. However, this loss was tolerated because of significant redundancy in the sensing array.

The experiment was performed with concrete cylinders and rectangular beams of standard dimensions employed in mechanical tests of concrete elements. The cylinders were of a length of 300 mm and of a radius of 54 mm. The beams were of 100 x 150 x 450 mm. We fabricated the cylinders and beams in our laboratory. The concrete mixture was of cement (Tolteca, Portland Compositon 30RRS), gravel of ¾", sand and water. The proportion between these components was 1:2.35:2.86:0.96.

In the first series of experiments, the optical fibers were put in the mold of a cylindrical form with no protection elements. We employed nine optical fibers of the same type in each cylinder. The extremes of the optical fibers were fixed outside the mold, so that the fibers were distributed quasi-uniformly over the cross-section of the cylinder and they were parallel to the cylinder axis. The mold was filled with fresh concrete mix and cured for 28 days. Then we removed the mold and visually inspected the concrete cylinder with embedded fibers, and measured the optical transmission of the fibers.

This series of experiments was carried on with eight different types of silica multimode optical fibers of cladding diameter ranging from 125 mm to 400 mm and plastic jacket of a diameter from 250 to 730 mm, respectively. Visual inspection showed that in all cases the fibers were displaced with regard to their initial position in the cylinder (Fig. 3, a). The maximum survival rate, of about 80 %, was observed in the fibers of the largest diameter (400/730 mm).



a) **b)**

Fig. 3. Fabricated concrete cylinders with embedded optical fibers: (a) – with fibers that were embedded without any protection, (b) - with fibers that were protected by plastic tubes when filling the mold with concrete mix

The second series of experiments was performed with fibers protected by plastic (PVC) tubes of a diameter of 6 mm and wall thickness of 0.5 mm. The same eight types of optical fibers were employed in the experiment. The plastic tubes were removed immediately after filling the mold with concrete mix while the mix was still fresh. The concrete mix filled the empty space around the optical fibers and fixed them in the concrete cylinder. In this case, the optical fibers remained in their initial positions (Fig 3, b). The maximum survival rate of the fibers was of 90 %. Similarly to the previous case, it was observed in the fibers of the largest diameter (400/730 mm).

4. Effect of load and cracks in concrete elements on the optical fibers

The concrete beams with embedded optical fibers were subjected to progressive mechanical load using the standard test paradigms. Each beam had an array of four identical silica optical fibers of cladding diameter 400 mm and jacket diameter of 730 nm (Thor Labs, FT-400-URT). One fiber was embedded at the top and three others at one plane at the bottom of the beam. The optical transmission of each fiber of the array was continuously monitored using the experimental arrangement described in Section 2. The load was progressively increased by 50 kg increments. The concrete beams with embedded optical fibers were subjected to progressive mechanical load using the standard test paradigms. The observed change of optical transmission with load is shown in Fig. 4.

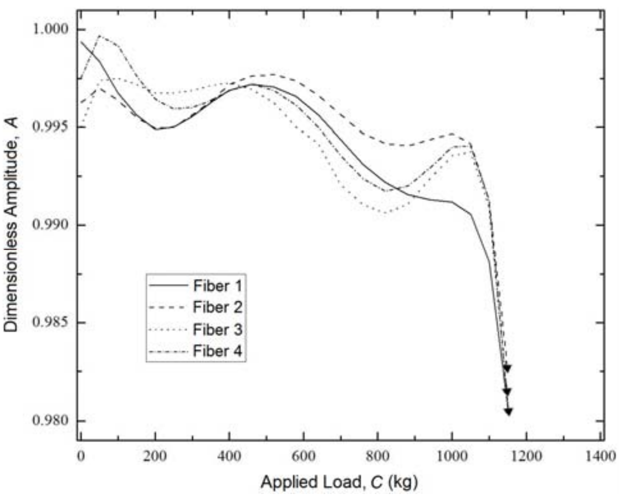


Fig. 4. Dimensionless optical transmission of four optical fibers of the sensor array against applied load.

The graphs in Fig. 4 show a small variation in optical transmission (>1%) with load until the load of about 1,200 kg is reached. We attribute these small variations to progressively increasing strain of the concrete beam and resulting alteration of the fiber geometry, in particular its microcurvature. Although the optical transmission varies with strain, the variation is of an oscillatory character. Therefore, no unique relation of optical transmission with strain can be established. Under the load of 1,200 kg, all graphs in Fig. 4 show a drastic decrease in optical transmission. This decrease is caused by breaking of the optical fibers which in turn is caused by cracking of the concrete beam under excessive load.

Experiments with optical fibers of small diameter (125 mm) revealed their tendency to slip in the strained concrete beam. However, the optical fibers of large diameter (240…425 mm) did not show any slippage under strain.

Conclusions

This sensor system successfully detects cracks in concrete elements which appear under excessive load. It employs sensor arrays of conventional communications-grade multimode optical fibers embedded in concrete. In this work, we demonstrated the operation of the present sensor system with the optical fibers of a relatively large diameter. However, the optical fibers of smaller diameter can be successfully used for the same purpose in this sensor system provided the surface of the plastic jacket of the fiber is sufficiently uneven so that the optical fiber does not slip in the concrete element under strain. The present sensor system is simple, robust and non-expensive. Due to these distinctive features it has many potential applications as cost-effective alternative to more precise but also expensive structural health monitoring systems.

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